Expanding the Kepler Legacy: Drift Scan Observations to Significantly Improve Kepler Astrometry

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Abstract

While the primary science goal for the Kepler mission is the detection and characterization of terrestrial and giant exoplanets through ultra-precision photometry, the telescope is theoretically capable of collecting ~2 milli-arcsecond precision relative astrometric data. This single measurement precision when combined with the few thousand epochs collected by the mission each quarter over its lifetime (> 40000 observations to date), means Kepler should be sensitive to Jupiter-mass planets and brown dwarfs around some of the nearest stars in the input catalog in addition to parallax and proper motions for the closest KOIs. Unfortunately, the Kepler PSF is out of focus and painfully undersampled with each pixel at 3.98 arcseconds/pixel. This combined with instrumental effects such as temperature/focus changes and CCD crosstalk have made it difficult to reach the predicted milli-arcsecond astrometric stability across multiple, continuous Kepler quarters. Even some of the red giant stars, the systematics are ~80 mas and above and repeat annually. This prevents the estimation of parallaxes and planetary orbits but not stellar proper motions. Utilizing the remainder of the Kepler mission in 2-wheel mode we propose to take some time to collect additional dithered images of the Kepler field at all four orientations in order to construct detailed point spread functions as a function of channel and position within a channel.

Expectations

If we assume that the precision goes as FWHM/(2*SNR) (Monet et al. 2010), then while the FWHM of a star in the Kepler FOV is 5-6 arcseconds, the high SNR (~10000, if the star is bright and isolated) allows the theoretical single measurement precision to be < 2 milli-arcseconds. If we then assume only random measurement noise over the length of the mission and a total of ~40000 measurements, the mission precision could be a factor of 200 less than the single measurement precision. Assuming a final measurement precision of 0.2 mas and an input list of thousands of M stars emulating those found within 25 parsecs but at random distances expected to be found in the Kepler field, we estimate that there is a significant sample of a hundreds of stars for which Kepler could astrometrically detect Jupiter mass planets with 3.5 year orbits (see Figure 1). Much like the Kepler KOIs these stars would benefit from follow-up observations with direct imaging and radial velocities and represent a separate and unique sample of planetary systems because these planets do not have to be transiting their host stars.

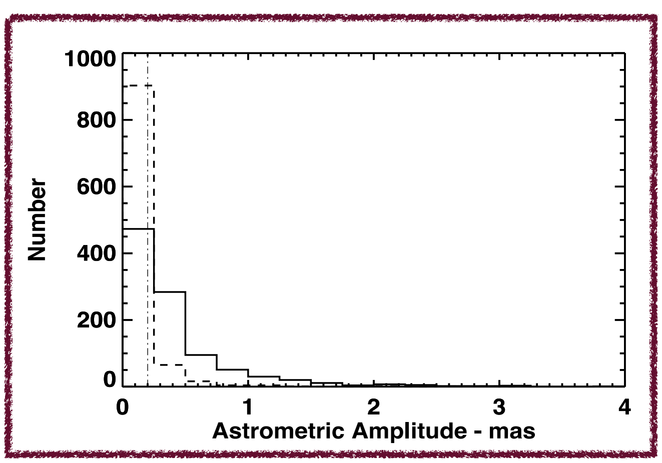

Figure 1 - Histogram of the astrometric signals of planetary and brown dwarf companions in 3.5 year orbits around a representative set of M dwarfs in the Kepler field. IF we are able to reach astrometric precisions of < 2 milli-arcseconds, then Kepler has the potential of detecting a few hundred additional very low-mass companions.

In addition, there are very few stars in the Kepler field that currently have precise (σ<10%) trigonometric parallaxes and accurate proper motions. The KOI stars would greatly benefit from precise estimates of their distances as this factors in to many of the observed and derived physical parameters both the host star and the planetary candidates. With the many new and exciting Kepler discoveries it is the trigonometric distances that have become highly sought after by the Kepler team and the exoplanet community.

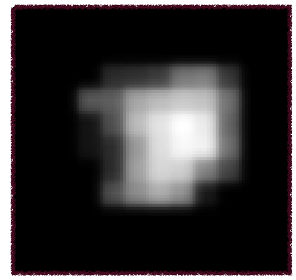

Figure 2 - Postage stamp image of a typical Kepler target.

The Challenge

Before even looking at the Kepler astrometry, we know there are going to be challenges to extracting stable stellar positions from this impressive data set. The large Kepler plate scale of 3.98 arcsecond/pixel (see Figure 2) and the crowded stellar field (by design of course) will complicate the astrometry as nearby fainter stars could bias the astrometric data regardless of whether they exhibit photometric variability. This is because there is a component of proper motion between all the stars over the duration of the mission. The cause of the proper motion is due to the intrinsic motions of the stars themselves as well as the differential velocity abberation (DVA, Kepler Instrument Handbook, Cox 1997). The DVA has a period of one year and an amplitude of ~150 mas.

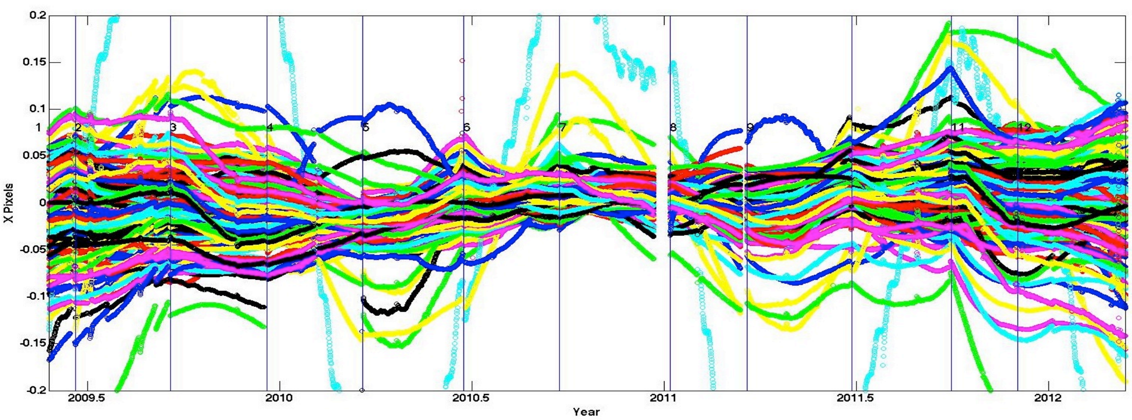

Figure 3 - Plot of the first moment centroid positions in the x-axis only of ~200 red giant stars over 12 quarters. All of these stars lie in channel 32 in the first quarter and their astrometric signatures have been normalized by their median value. The flattest of these curves have variations of ~100 mas. These curves do show some repeatability with common seasons (same channels) suggesting pixel phase variations as a possible culprit. The vertical lines represent the different quarters. The effect from DVA has been subtracted from these curves.

The Problem

The Kepler team provides first moment centroids (MOM_CNTR) of each star as part of their public data product. When we plot the pixel positions of a sample of red giants (Channel 32, Quarter 1, see Figure 3), the issues that have plagued previous attempts at utilizing the Kepler astrometry become clear. We have stitched the quarters together using the median of the offset of each end of one hundred data points. We have also removed a linear term to the resulting pixel positions to account for any slope introduced by the stitching process as this is just for studying the individual astrometric trends and not for comparing the relative position of the stars. While we can remove those red giants with the largest variations as obvious candidates for intrinsic or background stellar variability, even the “flattest” giants show variations whose origins whether astrophysical or instrumental have not yet been identified. The giants exhibiting the smallest positional variations over these 12 quarters are still varying by ~0.02 pixels or 80 mas which is much larger than the anticipated long-term precision of a few mas. Note that these variations are AFTER we have subtracted the POSS_CORR term from the Kepler provided first moment positions.

Focus Change?

If we replot Figure 3 but this time normalize each quarter of astrometry by the median value within that quarter we notice that some of the quarters exhibit larger variations than others (i.e.. Q 3, 7, 11 vs. Q4, 8, 12. see Figure 4). When we compare this to plots of variations in the focus there seems to be a cyclical correlation between the focus/temperature variations.

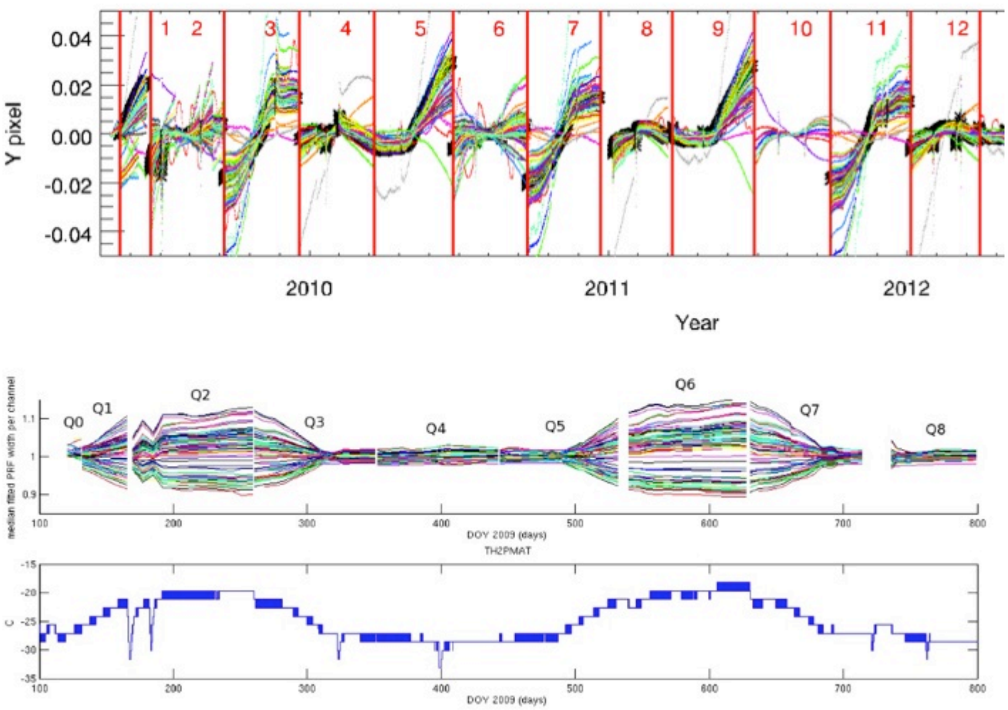

Figure 4 – Plot of astrometry of 100 red giants stars normalized by the median in each quarter compared with the values of the width of the PRFs and the spacecraft temperature from the Kepler instrument handbook.

Stellar Crowding?

It is currently not clear to what degree stellar crowding affects the stability of the stellar positions over multiple quarters. Figure 5 shows the astrometric positions of KIC 5698236 which exhibits astrometric variations (amplitude ~0.02 pixels = 80 mas) despite appearing to be a single star in both the high contrast Keck/NIRC2 AO image (5” across, Ciardi private com) and in the shallower Robo AO image (1’ across, Baranec et al. 2013). Therefore, while larger scale variations (> 0.07 pixels) may be due to nearby star contamination, which does not always explain these smaller scale variations.

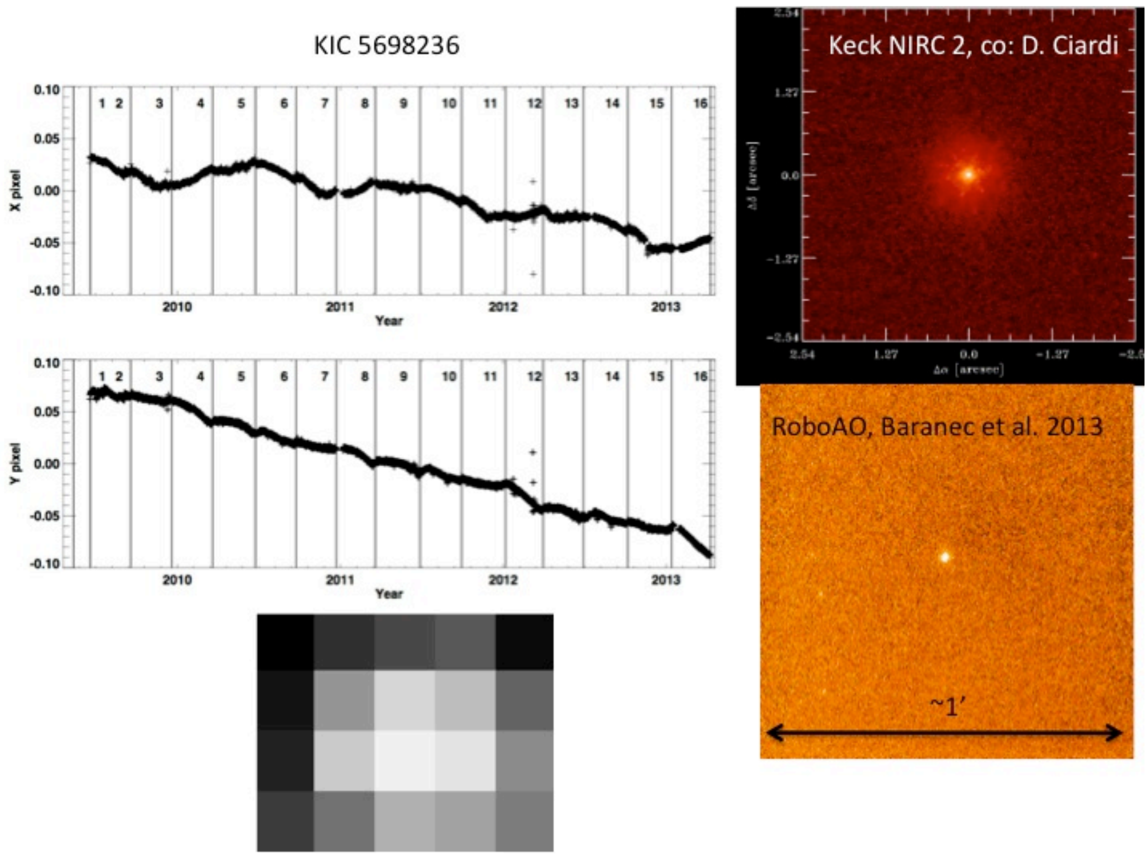

Figure 5 – Composite plot of Kepler astrometry for KIC 5698236. This star still shows significant annual astrometric systematics despite its clean stellar background as seen in both the high contrast Keck AO (D. Ciardi) and wider field Robo AO (Baranec et al. 2013) images.

Therefore, it is clear that in order to reach the multi quarter astrometric precision desired to use this data for trigonometric parallaxes and planetary purturbations, we must further investigate the source of these systematics and develop methods to mitigate the noise.

Some Good News: Extracting Stellar Proper Motions

In a world in which parallaxes cannot yet be obtained (see below), yet distance is a desirable piece of information, the reduced proper motion diagram (Figure 6) may provide an estimate. The concept is simple: proper motion becomes a proxy for distance. Statistically, the nearer any star is to us, the more likely it is to have a larger proper motion. The reduced proper motion diagram consists of the proper motion converted to a magnitude-like parameter plotted against color. While some nearby stars might have low proper motions, typically giant and dwarf stars are easily separated. The reduced proper motion diagram is analogous to an HR diagram. The more precise the proper motions, the better the discrimination between stellar luminosity classes. In transit work it is useful to know the luminosity class of a host star when estimating the size of the companion.

In the center of the Kepler focal plane (Channel 41), using positional normal points (generated by a home-built first-moment centroiding algorithm) from the optimum aperture image files acquired during three available quarters of Season 3, Benedict obtained positions with an average 1-s error of 3.5 milliseconds of arc (mas). He utilized UCAC4 proper motions with an average error of 4 mas yr^{-1} as prior information informing the Kepler astrometric modeling, and obtained final proper motions with an average error of 1.1 mas yr^{-1}. As a further test he carried out a similar study of a field further from the Kepler focal plane center (three quarters of Season 3, Channel 26). A mix of optimum aperture and full aperture positions (depending on crowding) yielded positions with an average error of 7.3 mas and proper motions with average error 2.4 mas yr^{-1}, again incorporating UCAC4 proper motions as priors. The degradation in astrometric precision is likely due to significant changes in the point spread function (PSF) over the Kepler field of view, and demonstrates the need for more sophisticated centroiding that is PSF-aware.

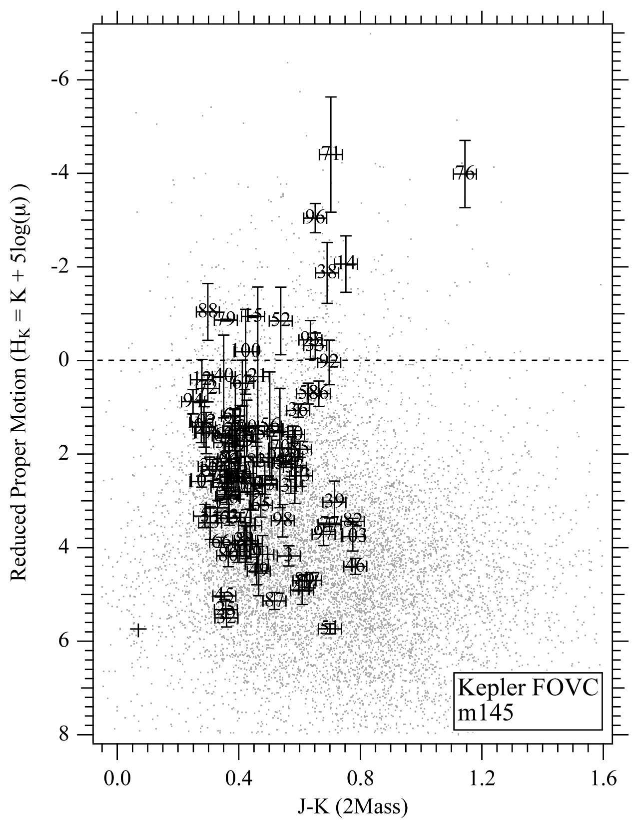

Figure 6 – A reduced proper motion diagram constructed by combining Kepler astrometry and UCAC4. Star 76 = KID 9020037 has a condition flag of Red_giant. Star 92 = KID 9086337 has no indication of luminosity class, but is likely a sub-giant. Star 88 = KID 9086251 hosts a planetary candidate. Plotted errors are 1-σ.

Finally, with simple centroiding unaware of PSF structure the season to season astrometry required for parallaxes presently yields positions with average errors exceeding 50 mas.

Next Steps

In an effort to try to understand and mitigate the systematic variations observed in the Kepler red giants, we have applied and are still developing additional methods for the position determination to the postage stamp images. These methods included Gaussian fitting, an independent first moment centroid and PSF fitting. As a check to the Kepler centroids, we employed a first moment centroid program (fwcentroid.pro) on the science images originally written for JWST target acquisition (M. Perrin author). Previous work on HST WFPC images suggested that PSF fitting would be able to account for intra-pixel variations often seen in images (Anderson & King 2000). For the PSF fitting, we used the PRF derived by the Kepler team which is divided into 5 pieces per channel and is available for each observing quarter. The PRF is fitted to the science target through the amoeba χ^2 minimization algorithm where the PRF is shifted by sub-pixel increments and then normalized to the same total flux as the science image prior to the $\chi2$ estimate. This method for position estimates is CPU intensive so only a subset of the science targets have been fully analyzed with this method. While Figure 7 shows that our estimate of the position of the star with the first moment method (light blue) is very similar to that provided by the Kepler team (black), the positions estimated with PSF fitting (light green) are quite different. In this particular plot the PSF fitted positions seem to follow the Kepler provided estimate of the differential velocity aberration, instrument breathing, etc. (POSS_CORR) quite closely implying a flat residual after subtraction. This is not typical for the remainder of the data sets.

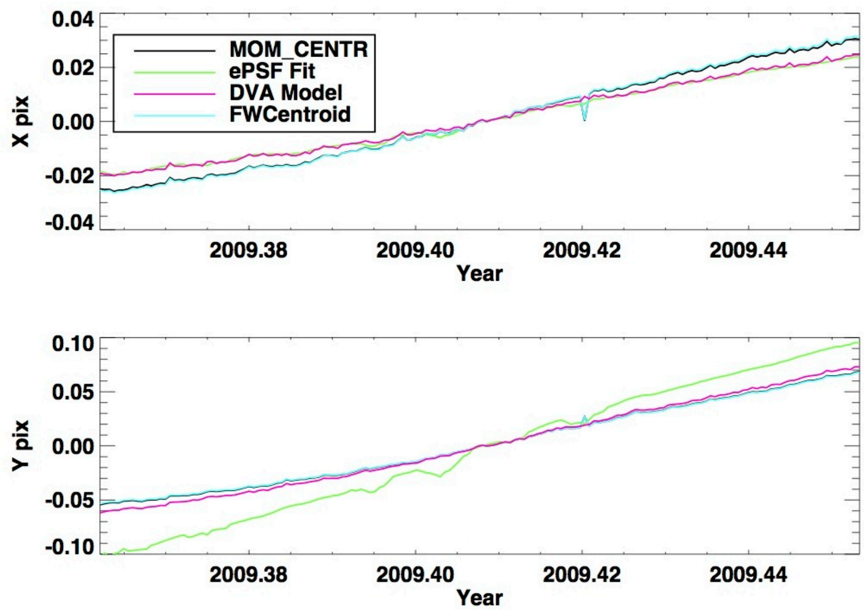

Figure 7 - Plot of the positions of a single red giant estimated over a single quarter using multiple methods: 1) the first moment centroids from the Kepler team (black), 2) the first moment centroids using another program (light blue), and 3) PSF fitting using an effective PSF (aka PRF) created by the Kepler team (light green). Also plotted is the Kepler team's estimate of the image drift due to differential velocity aberration (pink) and other instrumental effects such as spacecraft breathing and focus changes.

How the "New" Kepler Can Help with the Current Data

PSF undersampling is a common occurrence with space-based telescopes and is a known determent to precise astrometry (Anderson et al. 2001; Lauer et al. 1999). In the past, the method successfully employed to combat the resulting systematics produced by pixel-phase error in the undersampled PSF involves creating an effective PSF (or PRF). This is done with sets of *dithered* images of the astrometric field. Indeed, the Kepler Science Office collected dithered images during the commissioning phase of the mission. However, this was only completed at one spacecraft orientation. We wish to construct a library of dithered Kepler images at all four spacecraft orientations to be able to make robust PRFs for all the science targets in the Kepler field.

The Experiment

Given that we are repeating observations of the Kepler field, our experimental design will be similar to the primary Kepler mission. We will collect postage stamps of all the Kepler Science targets, stars with known trignomatric parallaxes (Henry et al. 2006) and proper motions (Lepine et al. 2007) as well as the previously identified red giant stars which we have been using as potential astrometric reference stars due to their presumed large distance. Because the download volume will be less of an issue, we will collect larger postage stamps (~20X20 pixels) than those obtained during the mission to be able to better assess the background contamination at the position of the star. We will use the long cadence (30 minute) exposure times to reproduce the data all ready in the archive. We would aim to repeat the ~120 dither positions in a way that would take advantage of the 1.4 degree drift of the telescope in two-wheel mode. Therefore, because we are dithering we are only concerned with the stability of the telescope pointing over the duration of the exposure.

With these dither images, we will then construct effective PSFs over multiple quadrants of each CCD (see Figure 8). The PRFs from the same part of the FOV will be compared between the four roll positions to help determine whether variations in the pixel sensitivities or telescope temperature/focus changes between the rolls is the source of the astrometry systematics. We will also use these PRFs to complete a program of robust PSF fitting to the science data in an attempt to mitigate the intra-pixel and focus variations and extract viable astrometric information from this formidable data set.

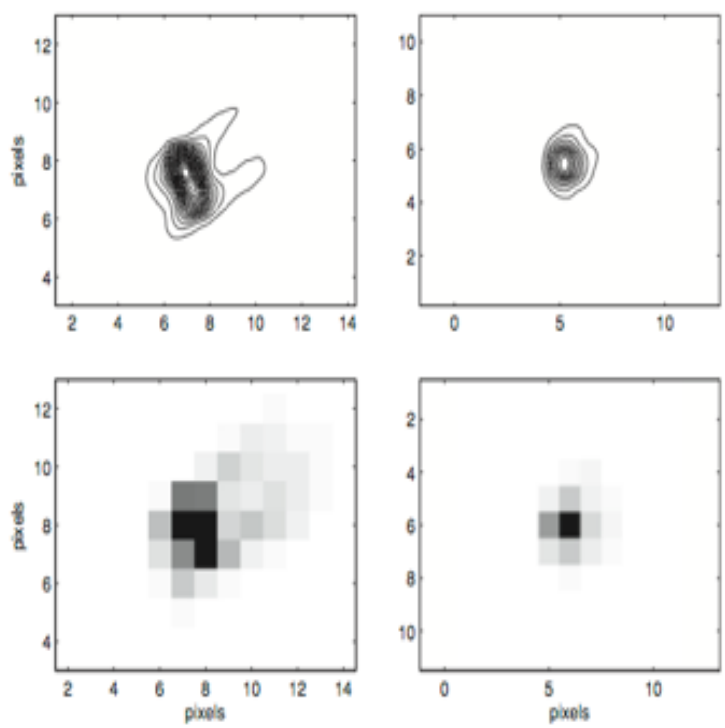

Figure 8 – Figure 1 from Bryson et al (2011) showng the effective PSFs (PRFs) created from the commissioning dithered images of the Kepler field. We will reproduce these PRFs for all four rotation angles of the spacecraft.

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